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ABSTRACT

This fifth in a series of six modules for a course titled Nondestructive Examination (NDE) Techniques II describes the fundamental concepts applicable to eddy current testing in general. The module follows a typical format that includes the following sections: (1) introduction, (2) module prerequisites, (3) objectives, (4) notes to instructor/student, (5) subject matter, (6) materials needed, (7) procedures, (8) data table, (9) reference materials, (10) test. (The course is one of fifteen technical courses for the second year of a two-year postsecondary curriculum in Nuclear Quality Assurance/Quality Control Technology.) (LRA)

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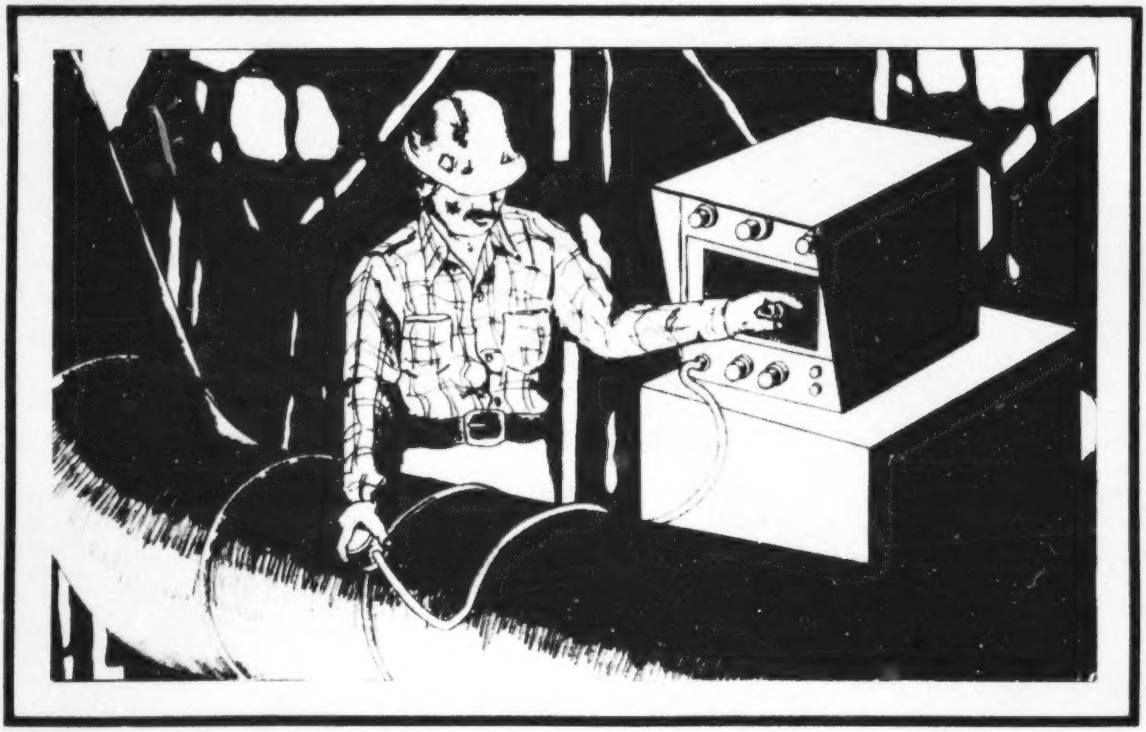
NUCLEAR TECHNOLOGY

COURSE 32 NONDESTRUCTIVE EXAMINATION (NDE) TECHNIQUES II

MODULE 32-5 Fundamentals of Eddy Current Testing



CE 024 297

GENERAL PHYSICS CORPORATION
Columbia , Maryland

COURSE MODULES

Course 32 Nondestructive Examination (NDE) Techniques II

Module 32-1 Fundamentals of Ultrasonic Testing
Module 32-2 Operation of Ultrasonic Test Equipment
Module 32-3 Fundamentals of Magnetic Particle Testing
Module 32-4 Operation of Magnetic Particle Test Equipment
Module 32-5 Fundamentals of Eddy Current Testing
Module 32-6 Operation of Eddy Current Test Equipment

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This module was prepared by John Espy, General Physics Corporation.

GENERAL PHYSICS CORPORATION

1979

INTRODUCTION

The nuclear QA/QC technician can have several responsibilities with respect to eddy current testing. The technician may qualify as an eddy current tester and perform product testing. Also, the technician may be responsible for monitoring or auditing eddy current testing performed by others.

Eddy current testing involves complex relationships between a variety of material properties and the effects of such properties on the electrical characteristics of a test coil. In any given test application, the relationship of specific material properties are established to permit measurement of those properties of interest. Even so, other material properties influence the test to some degree.

This module describes the fundamental concepts applicable to eddy current testing in general. It presents the electrical concepts, material properties and their effects, types of eddy current test coils, and principles of operation of eddy current testing systems.

MODULE PREREQUISITES

The student shall have completed all previous modules of Course 32.

OBJECTIVES

Upon completion of this module, the student/trainee can:

1. Define permeability, conductivity, magnetic flux density, inductance, and inductive reactance.
2. Relate the number and spacing of turns of a coil to the inductance or inductive reactance of the coil.

3. Recognize voltage plane and impedance plane graphs of a coil and describe the effects on coil voltage and phase angle as inductance of the coil changes.
4. Describe the generation of eddy currents.
5. Describe the effects on eddy current by (a) magnetic field strength, (b) test frequency, (c) conductivity of the test piece, and (d) permeability of the test piece.
6. Name at least five factors which affect conductivity of a metallic alloy.
7. Describe why eddy current testing of magnetic alloys must be performed with the alloy magnetically saturated.
8. Describe lift-off effects.
9. Describe fill factor effects.
10. Describe fall off effects.
11. Describe end effects.
12. Describe the physical arrangements of surface coils, including gap coils and spring loaded coils.
13. Describe the physical arrangements of encircling coils.
14. Describe the physical arrangements of inside coils.
15. Describe an absolute coil.
16. Describe the use of differential coils in the self-comparison technique and the external comparison technique.
17. Describe the impedance analysis method of eddy current testing.
18. Describe how phase analysis circuits can distinguish between the conductivity variable and the dimension variable.
19. Describe the vector point method of phase analysis.
20. Describe the ellipse method of phase analysis.
21. Describe the linear time base method of phase analysis.
22. Describe modulation analysis.

SUBJECT MATTER

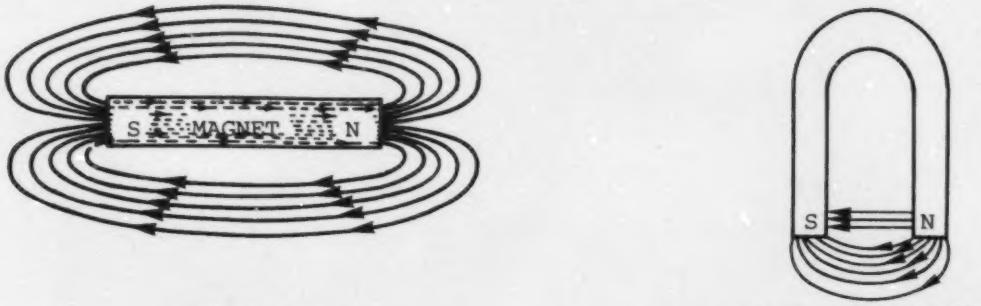
MAGNETIC PRINCIPLES

General

Eddy current testing uses the effect of the test piece on the inductive reactance of a test coil to determine properties of the test piece. It is necessary to understand inductive reactance, properties of materials which affect it, and the nature of the effects. Because all properties of materials which affect inductive reactance may be present in a given test piece, the nature of the effects of each property must be known if the test is to be used to detect only certain of these properties.

Magnetic Flux Density

We are familiar with common behavior of magnets. They attract certain materials (those which are magnetic) and do not attract other materials (those which are nonmagnetic). When two magnets are brought together, they attract in one orientation and repel when oppositely oriented. These behaviors of attraction and repulsion are due to magnetic lines of force which are present although invisible. Such magnetic lines of force are illustrated in Figure 32-5-1 for a bar magnet and a horseshoe magnet. The total number of magnetic lines of force is the magnetic flux. Because the term magnetic flux encompasses the entire field of lines of force, the term magnetic field is commonly used when speaking of the entire space within which flux exists. The number of magnetic lines of force per unit cross-sectional area is the magnetic flux density or, more simply, flux density. Thus, flux density increases as the number of magnetic lines of force increase within a given cross-sectional area. Likewise, flux density increases if somehow a given number of magnetic lines of force are squeezed into a smaller cross-sectional area.



BAR MAGNET HORSESHOE MAGNET

Figure 32-5-1. Magnetic Lines of Force

In 1819, Hans Christian Oersted, a Danish physicist, discovered that a definite relationship exists between electric current and magnetism. This relationship exists because electric current flow (current) generates magnetic lines of force. This flux is always at right angles to the direction of current. The direction of magnetic force (polarity) is dependent on the direction of current. Figure 32-5-2 illustrates these principles which can be determined for a straight conductor by applying the "right hand rule". By placing the right hand with the thumb in the direction of current, the fingers point in the direction of magnetic lines of force. It is noted that the lines of force are concentric to the longitudinal axis of the straight conductor.

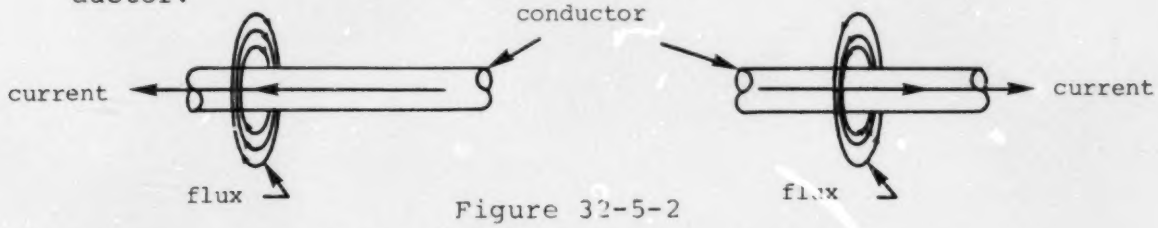


Figure 32-5-2

Magnetic Lines of Force in a Straight Conductor

If the straight conductor is formed into a circular loop, the magnetic lines of force at various cross-sectional areas around the loop combine such that the direction of the magnetic field is along the axis of the loop. As more circular loops are formed, this phenomenon produces a

definite field pattern which is discerned by applying the "right hand rule". Referring to Figure 32-5-3, if the right hand is placed around the loop such that the fingers point in the direction of current, the thumb points toward the north pole of the magnetic field.

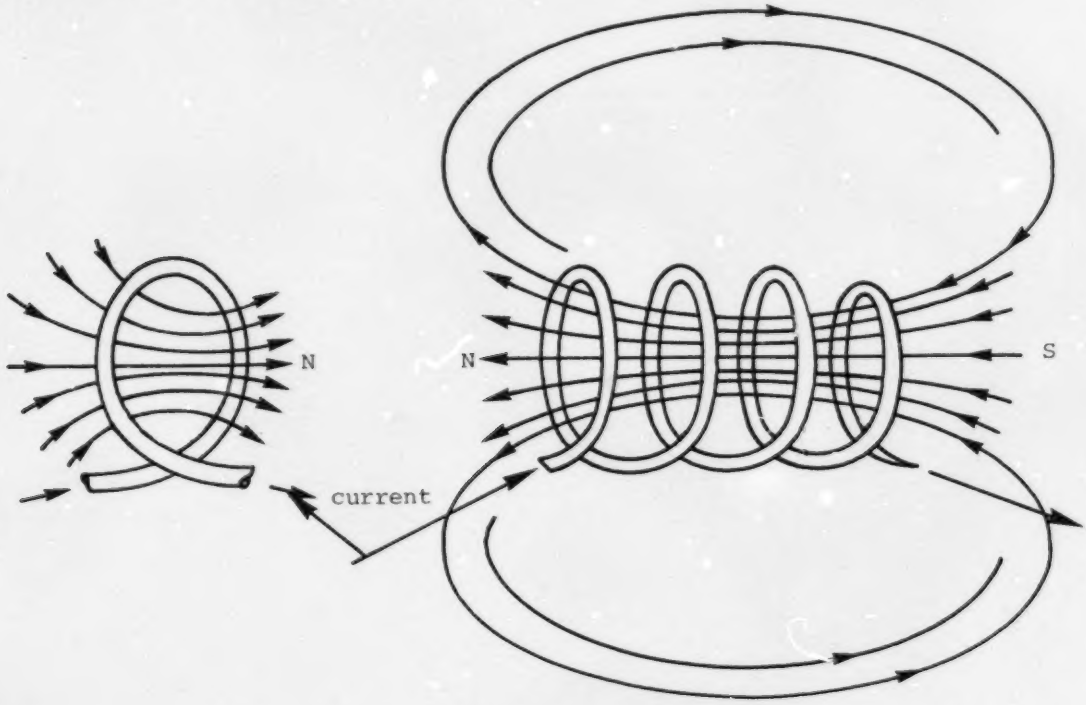


Figure 32-5-3. Flux in a Coil

The flux density at any given point within the magnetic field is a direct function of current. That is, as current increases, flux density increases. With constant current, flux density decreases with increasing distance from the coil. The decrease in flux density with distance is nonlinear. As explained later in this module, the decrease in flux density with distance affects the test depth of eddy current testing.

At a given distance from the coil and with constant current, flux density depends primarily upon the permeability of the material through which the flux exists. Permeability is a measure of the relative ability of a substance

to conduct magnetic lines of force as compared with air. The permeability of air is arbitrarily assigned as 1. Permeability of all other substances is measured in relation to the permeability of air.

Permeability is represented by the Greek letter mu (μ) and is expressed by Equation 32-5-1.

$$\mu = \frac{B}{H} \qquad \text{Equation 32-5-1}$$

where

μ = permeability

B = flux density in gauss

H = intensity of magnetizing force in gilberts per centimeter of length

By rearranging Equation 32-5-1, the flux density is the product of permeability and magnetizing force: $B = \mu H$. Using this form of the equation, one can imagine what happens to flux density if a material with high permeability is inserted into the coil in Figure 32-5-3. Insertion of material of higher permeability into the coil increases the flux density with all other factors unchanged. As indicated by Equation 32-5-1, the effect of permeability on flux density is large. If permeability doubles, flux density doubles. A tripling of permeability triples flux density, and so on. This large effect of permeability has serious implications for eddy current testing as described later in this module.

Inductance

Inductance is the characteristic of an electrical circuit that makes itself evident by opposing the starting, stopping, or changing of current. Repeating the prior sentence in a more simplified form, inductance is the characteristic of an electrical circuit which opposes a

change in current. Note that a change in current must occur for inductance to have effect. When the effect is present, it is always in opposition to the change in current. If current is increasing, inductance wants to prevent the increase. If current is decreasing, inductance wants to prevent the decrease.

An analogy of inductance is the mechanical movement of an object. Anyone who has pushed a car or a loaded wheelbarrow knows that it takes more work to start the object moving than it takes to keep it moving. This is because the object possesses inertia. Inertia is a characteristic of mass which opposes a change in velocity. Just as inertia opposes a change in velocity of a mechanical object, inductance opposes a change in current of an electrical circuit.

In 1831 in England, Michael Faraday performed experiments which demonstrated that current in one conductor is capable of inducing a voltage in another conductor. At the same time, Joseph Henry in New York discovered the property of self-induction of a coil. Work of these pioneers and later persons led to the development of electrical generators, induction motors, transformers, magnetic amplifiers, solenoids, relays, and other devices dependent upon induction.

Inductance is measured in units of the Henry. An inductor has an inductance of one henry if one volt is induced in the inductor when current through the inductor is changing at the rate of one ampere per second. The relationship of induced voltage, inductance, and rate of change of current is expressed by Equation 32-5-2.

$$E_{ind} = L\frac{\Delta I}{\Delta t}$$ Equation 32-5-2

where

E_{ind} = induced electromotive force (emf) in volts

L = inductance in henrys

ΔI = change in current in amperes occurring in Δt seconds.

Δt = time interval in seconds during which ΔI is determined

The process of induction can be envisioned as magnetic lines of force moving through a conductor and generating a voltage in the conductor by such movement. H.F.E. Lenz deduced that induced voltage is always a counter electromotive force (cemf). Lenz' Law states: "An induced emf always has such a direction as to oppose the action that produced it". Thus, a current varying in magnitude produces a varying magnetic field which sets up an induced emf that opposes the change in current producing it.

Inductance is largely dependent on magnetic coupling where magnetic coupling refers to the extent of the magnetic field passing through the inductor. A straight length wire has little magnetic coupling and therefore low inductance. The coil of Figure 32-5-3 has more magnetic coupling and a higher inductance. Coils with spaced loops have less coupling than coils with side-by-side loops. Double wound coils with overlapping loops have even greater coupling.

Magnetic coupling occurs whenever a conductor is located at any point within the magnetic field. If the conductor also carries the current which generates the magnetic field, as with a coil, self-coupling occurs and the resultant inductance is self-inductance. If the

conductor does not carry the current which generates the magnetic field, the coupling is mutual coupling and a mutual inductance exists. An example of mutual inductance is the transformer illustrated in Figure 32-5-4 primary winding generates the magnetic field which is coupled to the secondary winding.

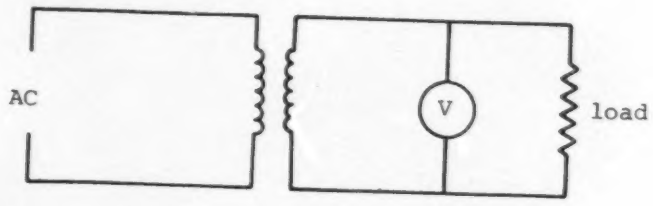


Figure 32-5-4. Transformer, Example of Mutual Inductance

Referring to Figure 32-5-4, the magnetic field of the primary winding induces a voltage in the secondary winding as measured by the voltmeter. The secondary voltage causes current flow through the load. One should note that current in the secondary winding also generates a magnetic field and this field is mutually coupled with the primary winding. In addition, each of the two windings has a self-coupling or self-inductance. Thus, there is self-inductance of each winding, mutual inductance from primary to secondary, and mutual inductance from secondary to primary. The interactions of such coupling are described later in this module using specific eddy current test probes.

Inductive Reactance

All materials offer some resistance to the flow of electric current through it. Good conductors, such as copper, silver, and aluminum, offer little resistance. Poor conductors, such as glass, wood, and paper, offer high resistance. The resistance of a material determines

if we classify it as a conductor or an insulator. Resistance of a material is the same whether direct current without ripple or alternating current flows through the material. It is this resistance used in Ohm's law expressed by E = IR, where E is voltage in volts, I is amperage in amps, and R is resistance in ohms. As illustrated in Figure 32-5-5, current and voltage are in phase in a purely resistive AC circuit.

Figure 32-5-5. In Phase Current and Voltage

If the resistor of Figure 32-5-5 is replaced with a coil, opposition to current stems from two sources. One source is the resistance of the wires which form the coil and the circuit. This resistance is relatively small because a good conductor is used. The second source of opposition to current is the inductance of the coil. This opposition stems from the self-induced voltage which is a counter electromotive force (cemf) according to Lenz's law. This cemf opposes the applied emf and the AC power supply sees an opposition to current flow.

The opposition to current flow is measured in ohms as previously stated. Rather than speaking of cemf of the coil in volts, we need a term expressed in ohms for the inductor's opposition to current flow. The term is inductive reactance. Thus, inductive reactance is the opposition offered by a coil to alternating current. It is designated

X_L and expressed by Equation 32-5-3. As indicated by the equation, if either frequency or inductance changes, inductive reactance changes.

$$X_L = 2\pi fl \qquad \text{Equation 32-5-3}$$

where

X_L = inductive reactance in ohms
f = frequency in hertz
L = inductance in henrys

Inductive reactance causes current to lag voltage. Unlike a purely resistive AC circuit where current is in phase with voltage, a reactive circuit causes an out of phase relationship. In a theoretical purely reactive AC circuit, current lags voltage by 90° as illustrated in Figure 32-5-6.

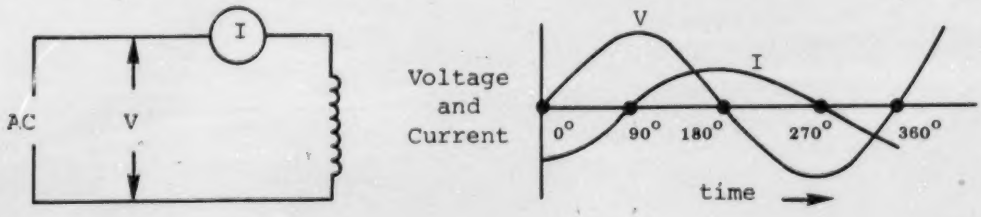


Figure 32-5-6. Purdy Inductive AC Circuit

In reality, inductive circuits have resistance if only from the resistance of the conductors which comprise the circuit. With respect to a coil, the windings of the coil have resistance and the coil has an inductive reactance. Thus, the coil can be diagramed as consisting of a pure inductor and a pure resistor in series where the value of the resistor is the resistance of the windings and the value of the inductor is the inductance of the coil.

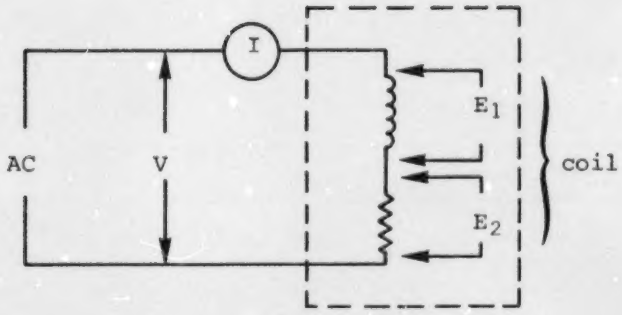


Figure 32-5-7. Schematic Diagram of Coil

Referring to Figure 32-5-7, it can be stated that current at any point in the circuit is the same at any instant of time. This is because there is only one current path in a series circuit. The voltages are designated as E, for voltage across the inductive component of the inductor and E_2 for voltage across the resistive component of the inductor. Using Ohm's law as the basis, E_1 must equal current times inductive reactance: $E_1 = IX_1$. Voltage across the resistor, E_2, must equal current times the resistance: $E_2 = IR$. However, current lags voltage in an inductive circuit. As illustrated in Figure 32-5-6, the current lags voltage by 90° in a purely reactive circuit. Thus, the E_1 voltage of Figure 32-5-7 must be ahead of the current; that is, E_1 leads the current. But E_2 must be in phase with the current as illustrated in Figure 32-5-5. Therefore, E_1 must be 90° ahead of E_2 or E_1 leads E_2 by 90°.

The relationship of E_1 and E_2 of Figure 32-5-7 is graphically plotted in Figure 32-5-8. This voltage plane graph identifies the phase relationship of E_1 and E_2 and represents the magnitude of these voltages by the length of the vectors. By vectorial addition of these two vectors, the actual voltage across the coil, Ec, is determined as

well as its phase. The true opposition to current is found by dividing coil voltage, Ec by the current, I. Such opposition is comprised of inductive reactance and resistance and is termed impedance and symbolized as Z. An impedance plane graph plots the X_L and R vectors to determine the magnitude and phase of impedance.

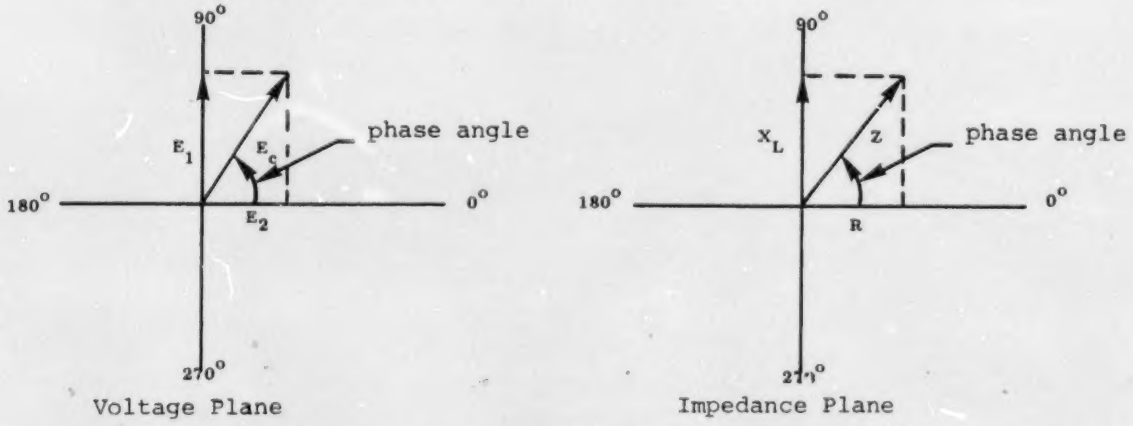


Figure 32-5-8. Voltage and Impedance Planes of a Coil

By studying the voltage and impedance planes of Figure 32-5-8, one can observe that as the ratio of inductance to resistance increases, the phase angle increases. In other words, if the inductive reactance of the coil increases while its resistance is constant, the phase angle increases. Likewise, if the inductive reactance of the coil increases while its resistance is constant, the coil voltage increases. Similarly, decreases in inductive reactance with constant resistance result in decreased coil voltage and phase angle.

Eddy Current Generation

If a conductor is brought into the magnetic field of an AC coil, a voltage is induced in the conductor. This induced voltage provides the force for current flow. We know that current must have a path for flow. The load on

the transformer in Figure 32-5-4 gives a path for current. But what happens if there is no path for current flow in the classical sense?

Referring to Figure 32-5-9, a metal is placed within the magnetic field of an AC coil. The metal has relatively low resistance. Since conductance is the opposite of resistance, the metal has a high conductance. Therefore, the metal is quite capable of supporting current flow but it does not offer a flow path in the classical sense. But, the metal offers a variety of flow paths within the metal itself. Consequently, current circulates within the metal. These circulating currents are termed eddy currents. Thus, eddy currents are induced currents which circulate within a conductor.

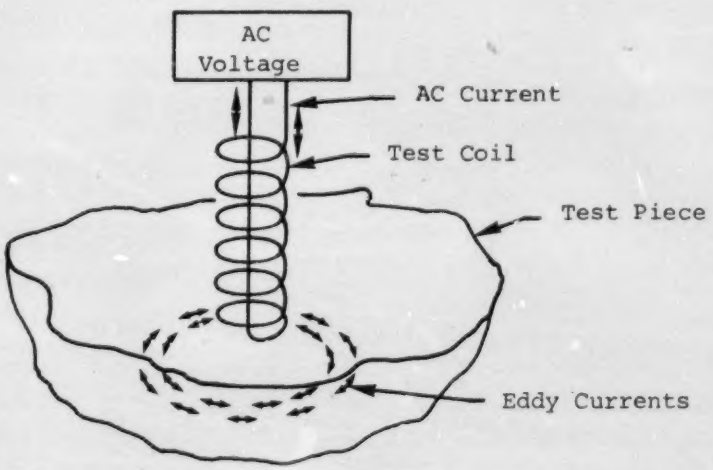


Figure 32-5-9. Eddy Currents

Eddy currents in a test piece generate their own magnetic field. The eddy current magnetic field is mutually coupled with the coil just as the coil's magnetic field is mutually coupled with the test piece. Thus, a number of variables affect the electrical characteristics of the circuits. In essence, anything that changes flux

density within the magnetic field of the coil affects the self-inductance of the coil. Measurement of the coil's electrical properties permits correlation with those things which affect the coil. The major difficulty is in the ability to discern which of the many properties are affecting the coil.

EDDY CURRENT PRINCIPLES

Basic Test Process

Eddy current testing is a nondestructive test method which measures material properties through the reaction of such properties to the test coil. The basic test system is illustrated by the block diagram of Figure 32-5-10.

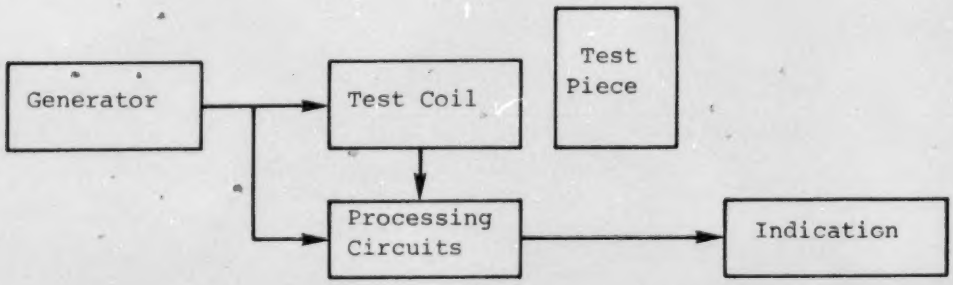


Figure 32-5-10. Basis Eddy Current Test System

Referring to Figure 32-2-10, the generator establishes an AC voltage at a desired frequency. The AC voltage is applied to the test coil and, in most applications, to the processing circuits to assist in making meaningful analysis of the electrical characteristics of the coil. The test coil induces eddy currents in the test piece. Properties of the coil and the test piece which affect magnetic coupling effect the inductive reactance of the coil. The processing

circuits measure the coil's electrical characteristics and either compare them with a standard or determine if they change. The comparison or change is processed in such a way as to enable determination of those test piece properties causing the effect. The result is indicated by meter, cathode ray tube, or strip chart recorder. The essential variables of the test are the type of coil, the applied frequency, the test piece properties, and the proximity of the coil to the test piece. For a given test system, all these essential variables are fixed except for test piece properties and possibly the proximity of test coil to test piece.

Factors Affecting Eddy Current Testing

The factors which effect eddy current testing and thus affect the test indication are broadly categorized as (1) penetration, (2) conductivity, (3) permeability, and (4) dimensions. Within each of these categories there are several factors which affect test results. These are described in subsequent paragraphs. In addition to these four categories, the test coil design affects the test. Test coil design is described separately in a later section.

Factors Affecting Penetration

The depth within a test piece at which eddy currents are sustained is affected by (1) strength of test coil's magnetic field in the test piece, (2) frequency applied to the test coil, (3) conductivity of the test piece, and (4) permeability of the test piece.

The test coil's magnetic field in the test piece decreases in flux density with increasing distance into the test piece. This is mostly because the flux generated by eddy currents opposes the inducing flux (Lenz Law). For a given test coil magnetic field, the strength of that

field seen by the test piece decreases with depth in the test piece as measured from the test coil. Likewise, changing the strength of the test coil's magnetic field changes the depth within the test piece where a given flux density exists. Therefore, as test coil field strength increases, depth of penetration increases.

Frequency affects the depth of penetration of the test piece due to "skin effect" which is common to all conductors. The magnetic field generated by current flow tends to force the flowing electrons toward the outer surface of the conductor. This effect increases as frequency increases. Therefore, the depth at which eddy currents exist is affected by frequency applied to the test coil. As frequency of the test coil increases, depth of penetration decreases.

Conductivity affects the magnitude of eddy currents which in turn affects depth of penetration. As conductivity increases, the magnitude of eddy currents increases which results in a larger magnetic field generated by the eddy currents. This larger field forces the circulating currents closer to the surface. Therefore, as conductivity of the test piece increases, depth of penetration decreases.

Permeability affects the flux density in the test piece supported by the test coil's magnetic field. As permeability increases, a larger flux density is permitted for a given test coil field strength. The larger flux density induces larger circulating currents whose own larger magnetic fields both force circulating current toward the surface and more greatly counter the test coil's magnetic field. Therefore, as permeability increases, depth of penetration decreases.

In summary, penetration is affected by coil field strength, test frequency, conductivity of the test piece, and permeability of the test piece. The effects are:

- As coil field strength increases, depth of penetration increases.
- As test frequency increases, depth of penetration decreases.
- As conductivity of the test piece increases, depth of penetration decreases.
- As permeability of the test piece increases, depth of penetration decreases.

Factors Affecting Conductivity of Test Piece

Conductivity is frequently expressed in terms of the International Amended Copper Standard (IACS). This highly pure copper standard is defined as having 100% conductivity. The conductivity of other materials is expressed as a percentage relative to this standard. For example, pure gold has an IACS conductivity of 73% and pure aluminum has 66%. Factors affecting conductivity include (1) chemical composition, (2) heat treatment condition, (3) cold working condition, (4) lattice defects, (5) temperature, and (6) flaws.

The chemical composition of a metal affects conductivity of that metal. Whether it is a pure element, such as pure aluminum, or an alloy, such as stainless steel, metals offer a definite conductivity which is dependent on the chemical constituents of the metal. Chemical constituency affects conductivity whether it is comprised of the desired alloying ingredients or undesired impurities. However, because other factors affect conductivity, a given metal's conductivity varies over a finite range due to the influence of other factors. Therefore, conductivity ranges of various metals can overlap. Nonetheless, a definite correlation exists between a metal's conductivity and its chemical composition. Conductivity of a few metals is indicated for illustration purposes in Figure 32-5-11.

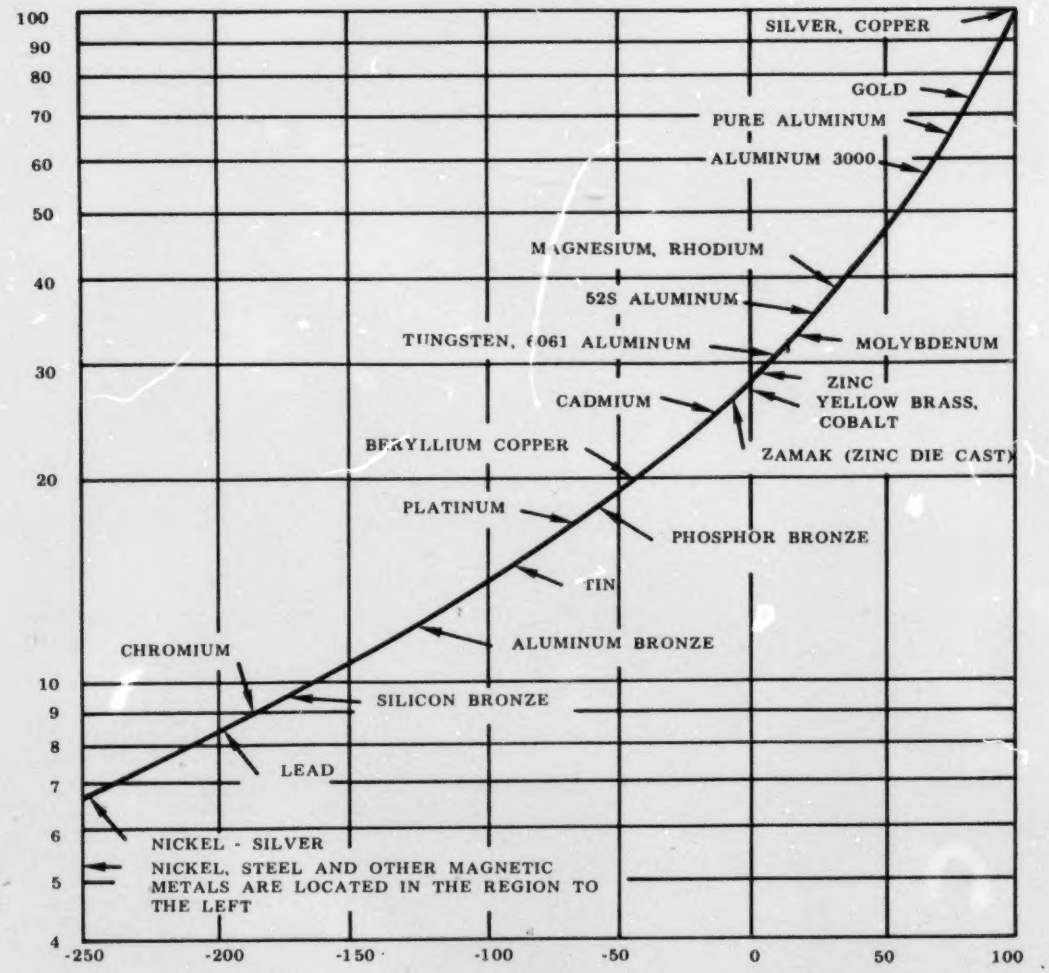


Figure 32-5-11. IACS Conductivity of Various Metals and Alloys Versus Eddy Current Readings

The heat treatment condition of metals and alloys determines the grain size, crystalline structure, and distribution of alloying ingredients and impurities within the grain pattern. All of these variables affect conductivity. In many cases, sufficient empirical data exist to permit determining the heat treatment condition by measuring conductivity.

Cold working of alloys distorts and disrupts crystalline lattices and grain boundaries. Such physical displacement affects the conductivity of the alloy.

Crystalline lattices can contain defects due to stressing, irradiation, and other causes. Such defects affect conductivity by altering the normal lattice structure.

For conductors, temperature inversely affects conductivity. That is, as temperature increases, conductivity decreases. In insulators there is an opposite effect. That is, as temperature increases, conductivity increases.

Flaws within the metal or alloy decrease conductivity in the area of the flaw. Any discontinuity in the crystalline structure is considered a flaw, such as porosity, inclusions, and cracks.

In summary, conductivity is affected by chemical constituency, heat treatment, cold working, lattice defects, temperature, and flaws. The exact effect is determined empirically through many experiments. Conductivity ranges of alloys sometimes overlap.

Factors Affecting Permeability of Test Piece

Values for permeability primarily depend upon (1) whether the alloy is magnetic and (2) for magnetic alloys, whether saturation occurs. Magnetic materials, such as iron and most iron alloys, have a relatively high permeability below saturation and low permeability above saturation. Because permeability is high and also nonlinear below saturation, permeability has the single largest effect on eddy currents within magnetic materials. For saturated magnetic materials and for non-magnetic conductors, permeability is relatively small and basically constant. Relative permeability of magnetic and non-magnetic alloys is illustrated in Figure 32-5-12.

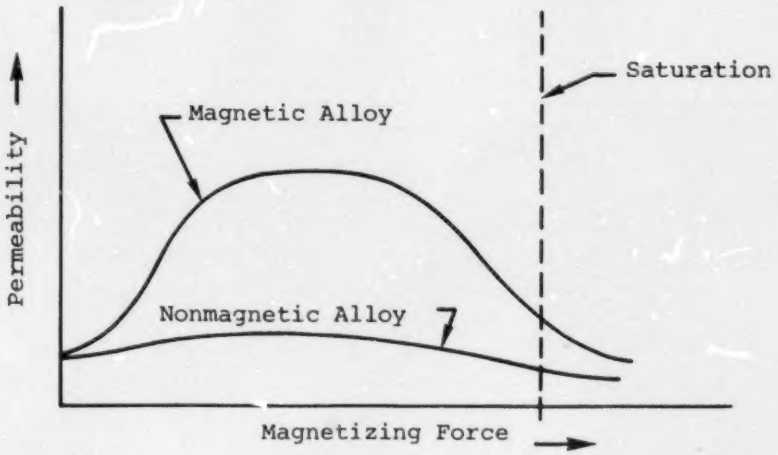


Figure 32-5-12. Relative Permeability of Magnetic and Non-magnetic Alloys

Review of Figure 32-5-12 reveals several important features with respect to eddy current testing. First, permeability can be considered relatively constant for non-magnetic materials regardless of the magnetic force. Second, permeability of magnetic alloys can be made relatively constant by saturating the alloy with an independent magnetizing force. In this manner, permeability would not vary with magnetizing force. Instead, internal stresses and lattice impurities would have the predominant effect on permeability. Thus, eddy current testing would be sensitive to internal stresses and lattice impurities.

Factors Affecting Dimensions

The dimensions associated with proximity of test coil to test piece, geometry of the coil, and geometry of the test piece are important with respect to eddy current testing. These dimensions affect the magnetic coupling between the coil and the test piece. As described previously in

this module, changes in coupling change the magnitude of eddy currents. Dimensional effects are manifested as "lift-off", "fill factor", "fall-off" and "end effect".

Lift-off refers to the large change in output indication which occurs as a test coil is withdrawn from a conductive test piece. It is due to the decrease in flux density within the test piece as distance from the coil increases. The lift-off effect is so great that a change of 0.001 inch in test coil to test piece distance is measureable. This phenomenon offers advantages and disadvantages for eddy current testing. For tests of conductive materials, it is a disadvantage because of the need to maintain essentially constant spacing from test coil to test piece. It becomes an advantage in tests of non-conductive coatings, such as paints, on conductive materials. Dry film coating thickness measurements use the lift-off effect to determine coating thickness as illustrated in Figure 32-5-13.

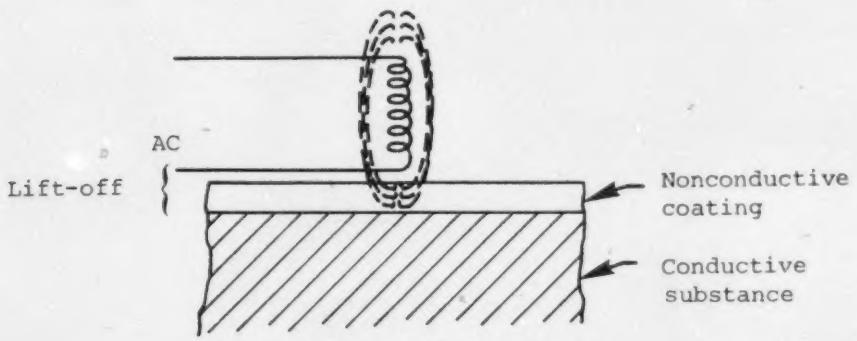


Figure 32-5-13. Lift-Off Effects Used for Coating Thickness Measurement

Fill factor is the equivalent of lift-off for encircling coils. As illustrated in Figure 32-5-14, fill factor expresses the extent to which circular product fills the

volume within the encircling coil. Fill factor is expressed as $\left(\frac{D1}{D2}\right)^2$ and is always less than unity. A reduction in fill factor reduces sensitivity of eddy current testing. It is noted that a noncentering of the circular product within the coil affects fill factor.

Fall-off refers to the falling off of field strength at a distance from a test coil due to coil dimensions and shielding. The primary dimensions affecting fall-off are pole size and spacing. This is illustrated in Figure 32-5-14 for two pole sizes of equal spacing. The larger poles provide for greater penetration or less fall off.

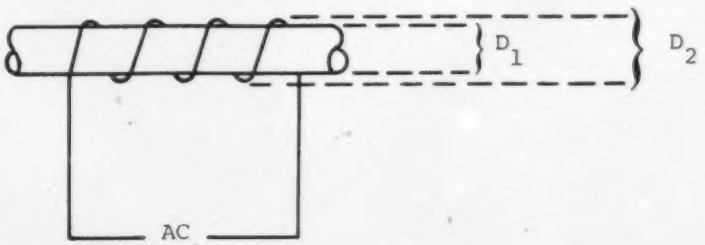


Figure 32-5-14. Fill Factor

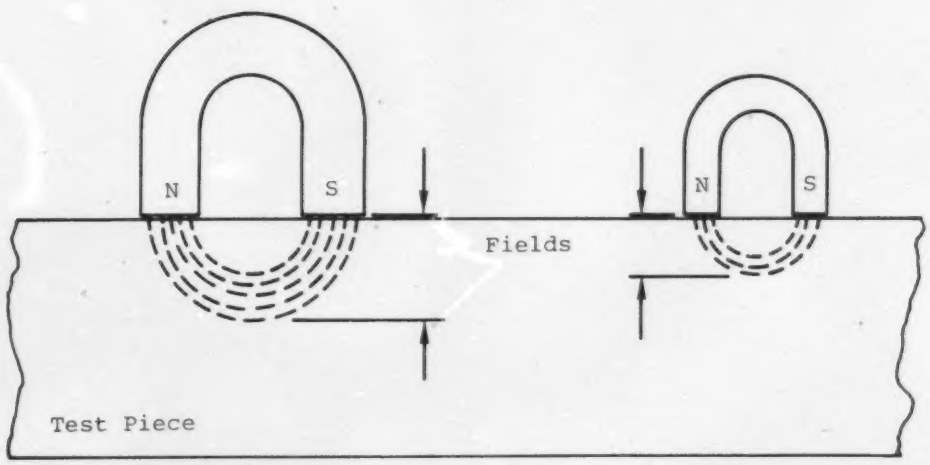


Figure 32-5-15. Fall-Off

Fall-off is also affected by the shielding within a coil. Shielding pinches or directs the field such that fall-off occurs rapidly with distance from the coil. An example of shielding is illustrated in Figure 32-5-16.

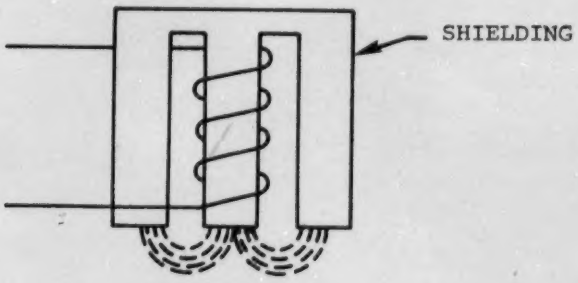


Figure 32-5-16. Shielding

End effect refers to the effect on eddy currents by an abrupt change in geometry of the test piece. Such abrupt changes are illustrated by edges, corners, holes, ends, etc. At such points, the coil's field is distorted by the test piece-to-air boundary. This reflects as an indication which can mask or obscure signals from material properties which are intended to be detected.

TEST COILS

General

The sensor for eddy current test systems is the test coil. Test coils are available in many arrangements and sizes in order to be adaptable to test piece size and configuration. Test coils may be single or double coils. Their arrangement can permit placement around, within, or on the test piece. Double coils include differential coils. Coils are wound on nonconductive material such as plastic although shielding may be used.

Surface Coils

Surface coils are designed for use on the surface of the test piece. Surface coils may be contacting or non-contacting and are shaped to match the contour of the test piece.

Surface coils are typically "gap" coils or spring-loaded coils. The gap coil uses magnetic shielding to confine the field to the gap between the shielding members. This is illustrated by Figure 32-5-16. Spring-loaded surface coils use spring pressure to maintain surface contact and, thereby, minimize lift-off effects. The spring loaded coil, which is illustrated by Figure 32-5-17, may be direct contacting or designed to hold the coil a fixed distance from the surface.

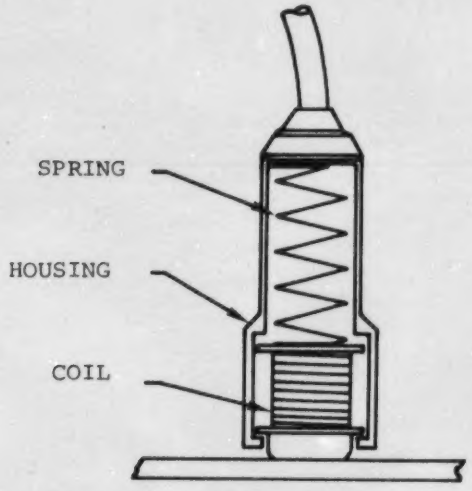


Figure 32-5-17. Spring-Loaded Surface Coil

Encircling Coils

Encircling coils encompass the test piece about an axis of the test piece. It is shaped similar to the shape of the test piece. That is, the encircling coil may be circular, squared, or rectangular. A circular encircling coil is illustrated in Figure 32-5-18.

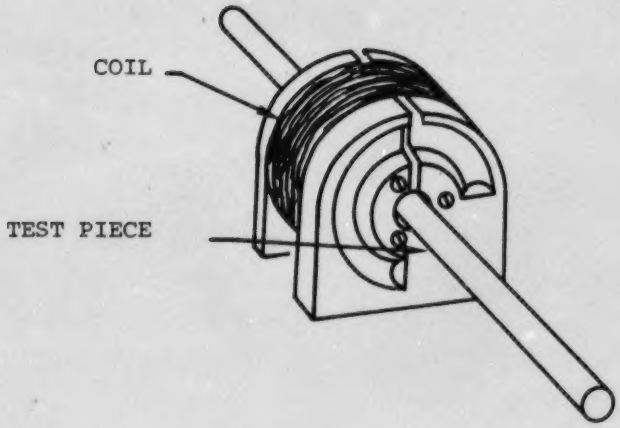


Figure 32-5-18. Encircling Coil-Circular

Inside Coils

Inside coils are arranged to permit insertion of the coil within the test piece. The most common application is for testing of tubing which requires a circular inside coil. Other shapes, however, are possible. Figure 32-5-19 illustrates an inside coil.

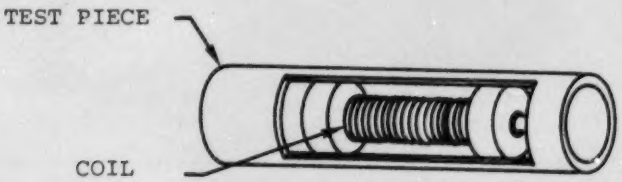


Figure 32-5-19. Inside Coil Circular

Absolute Coil

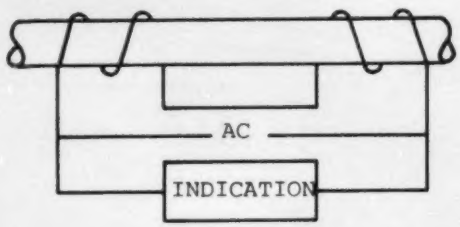
An absolute coil is one which tests the test piece without comparison to a standard. An absolute coil may be a contact coil, encircling coil, or inside coil. It may be single wound or double wound. It is termed absolute

because it tests the material adjacent the coil without referencing the eddy current effect to anything else. Single and double absolute coils are illustrated in Figure 32-5-20.

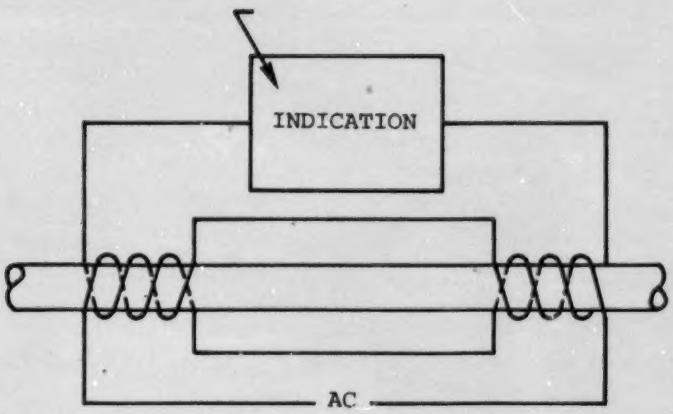
Figure 32-5-20. Absolute Coils

Self Comparison Technique

The self comparison technique uses differential coils to test two discrete areas of the test piece. If test piece properties are identical under each coil, the outputs of the two coils cancel. If a slight difference in properties exist under the coils, an output results. The differential coils may be single or double coils as illustrated in Figure 32-5-21.



Single Coils - Differentially Wound



Double Coils - Differentially Wound

Figure 32-5-21. Self Comparison Coils

External Comparison Technique

External comparison technique uses a reference standard for comparison with the test piece. Differential coils are used as in the self comparison technique but one coil measures the test piece and the other coil measures the reference standard. Differences in properties between the test piece and reference standard result in an output. Figure 32-5-22 illustrates the external comparison technique.

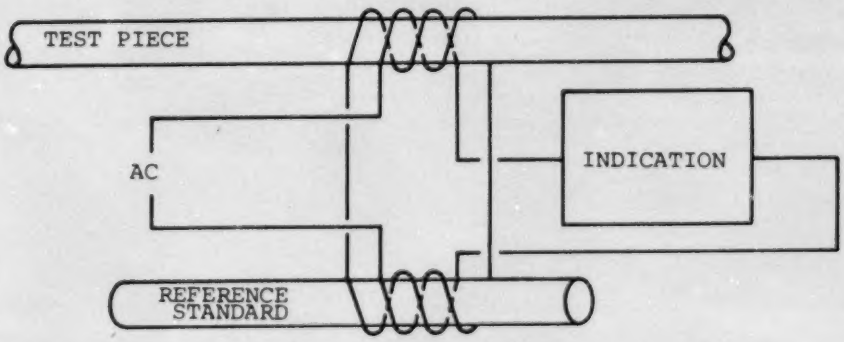


Figure 32-5-22. External Comparison Coils

PROCESSING CIRCUITS AND INDICATION

General

Figure 32-5-10 illustrates that processing circuits evaluate the effect of the test piece on the test coil and provide a meaningful indication (readout). Figure 32-5-8 pictures the measureable characteristics of the test coil as consisting of (1) impedance, (2) phase angle, and (3) combination of either voltage and phase angle or impedance and phase angle. Processing circuits measure these characteristics and translate the results into useful indication. Thus, processing circuits are classified as either impedance analysis or phase analysis. In addition, a specialized form of analysis exists which is termed modulation.

Impedance Analysis

Eddy current testing which employs impedance analysis is based on changes in the impedance of the test coil. Changes in impedance of the test coil changes current by the relationship of $I = \frac{E}{Z}$. The processing circuits convert the change in current to a meaningful indication. Impedance analysis is relatively simple and is used by many portable eddy current testers. Common applications include measurement of conductivity and tests for flaws.

Conductivity testing is used for (1) metal sorting, (2) hardness measurements, (3) heat treatment condition measurements, and (4) coating thickness measurements. Metal sorting consists of confirming or determining material identity by measuring its conductivity. As previously described, those materials which have overlapping conductivity ranges cannot be sorted with assurance by conductivity alone. Thus, conductivity testing often will not sort various grades of the same alloy.

But, for metals not having overlapping conductivity, eddy current testing using impedance analysis provides a quick means of determining the type of metal. Such a test is useful in detecting material mixups. Eddy current conductivity testing used for hardness measurements is based on decreases in conductivity as hardness increases. For specific alloys whose conductivity to hardness relationship has been well established, impedance testing can be calibrated to indicate hardness of the alloy. Similarly, where conductivity for each possible heat treatment condition of a given alloy has been well established, eddy current testing can verify which heat treatment condition exists. This is based on the change in conductivity with changes in metallurgical conditions of the alloy which are established by the heat treatment. For example, an alloy, whose hot worked conductivity is 72% IACS and whose hot worked and quenched conductivity is 53% IACS, can be sorted by heat treatment condition by impedance testing.

Impedance testing of coating thickness uses conductivity effects for conductive coatings and lift-off effects for nonconductive coatings. For conductive coatings, such as chrome plating, the frequency is set to give penetration just beyond the expected coating thickness. As actual coating thickness varies, conductivity seen by the test coil varies and, thus, the readout is proportional to coating thickness. As previously described, nonconductive coating thickness is measured by changes in output indication caused by variations in lift-off. For such measurements, the substrate must be conductive.

Impedance testing for flaws is a gross testing system which detects changes in the coil's impedance. Due to other factors which affect the coil's impedance, it is difficult to detect minute flaws. In such tests, it is important to minimize the influence of controllable factors

such as frequency and lift-off or fill factor variations. Also, it must be recognized that penetration depth is limited and flaws deeper than the penetration depth are not detected. Impedance flaw detection is based on the disruption of eddy current paths caused by the flaw and the corresponding reaction on the coil's impedance. Minute flaws can produce such minor changes as to be indistinguishable from changes in other material properties which affect the test coil.

Phase Analysis

Phase analysis is more complex than impedance testing but has the capability of separating the conductivity variable from the permeability and dimension variables. As described later, permeability and dimension variables are inseparable. Phase analysis circuits typically evaluate the combination of either voltage and phase angle or impedance and phase angle. It uses differential coils arranged for either self comparison or external comparison. The indication represents the phase change and voltage or impedance change between the differential coils.

Referring to Figure 32-5-22, the output of the coils are equal provided the properties of the test piece are identical to those of the reference standard. With this condition, the indication is zero due to the differential arrangement of the coils. The question becomes what happens to the output as conductivity, permeability, and dimensions of the test piece change with respect to the reference standard.

If all factors of a number of test pieces are held constant except that each test piece has the different conductivity, the composite plot illustrated in Figure 32-5-23 is obtained. This plot connects the ends of the composite voltage vectors for each conductivity value of various test pieces. That is, it connects the voltage

plane Ec vectors illustrated in Figure 32-5-8. Increasing conductivity causes the plot to move from A to B in Figure 32-5-23.

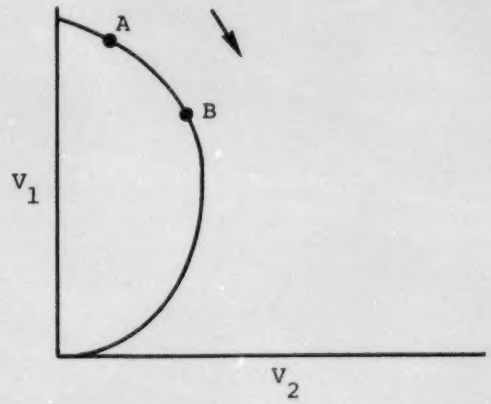


Figure 32-5-23. Ec Curve with Conductivity Changes

If conductivity of the test pieces is held constant and either dimensions or permeability are permitted to vary, a plot similar to that in Figure 32-5-24 is obtained. In this case, changes in either dimensions or permeability yield the same results. That is, an increase in either moves the plot from C to D.

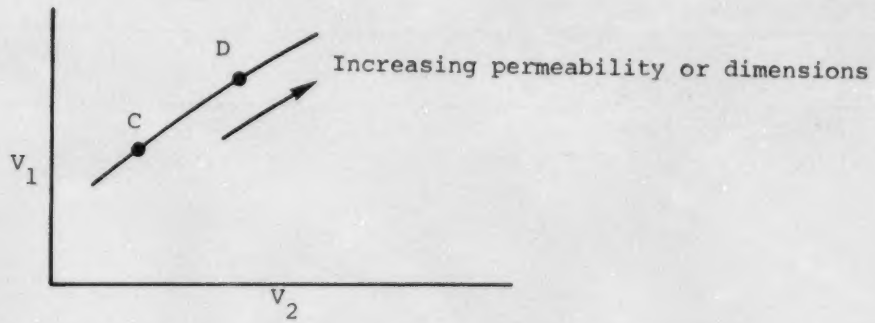
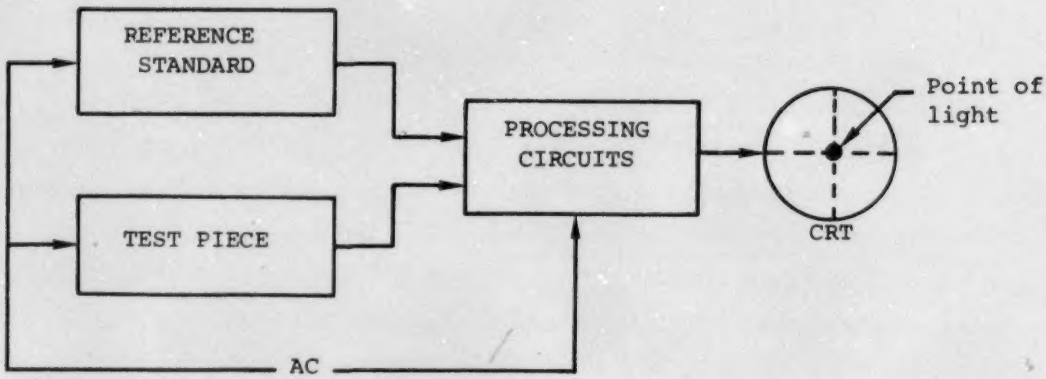


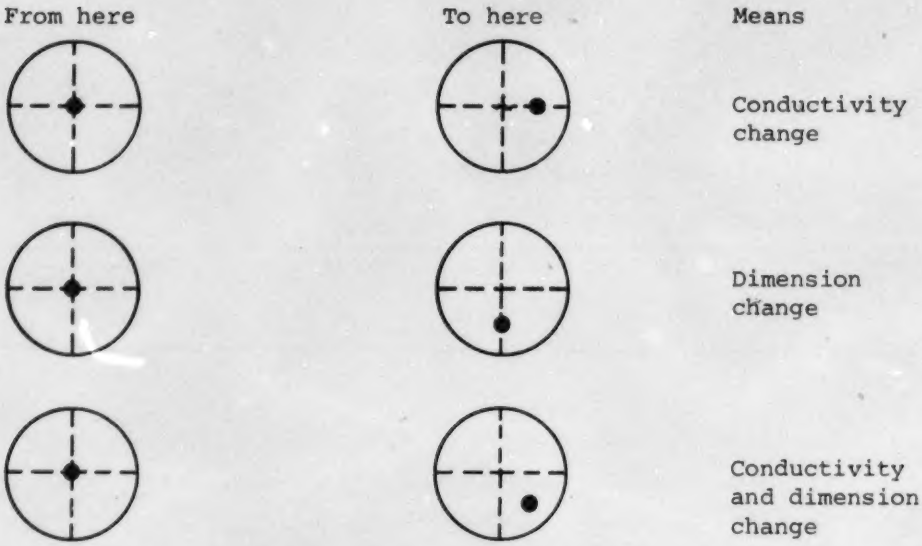
Figure 32-5-24. Ec Curve with Permeability and Dimensional Changes

By superimposing the plots of Figures 32-5-23 and 32-5-24, an important fact is realized. The direction of the coil's output with conductivity changes is essentially at a right angle to the direction of the coil's output with dimension and permeability changes. This fact permits processing circuits to separate the conductivity variable from the dimension and permeability variables. The dimension and permeability variables are inseparable because they cause a change in coil output in the same direction. Processing circuits use (1) vector point method, (2) ellipse method, or (3) linear time base method for phase analysis.

Phase Analysis - Vector Point Method

The vector point method of phase analysis controls a point of light on a cathode ray tube (CRT) as illustrated in Figure 32-5-25. The processing circuits supply a voltage representing the conductivity variable to one axis of the CRT (horizontal axis in the figure) and supply a voltage representing dimension and permeability variables to the other axis of the CRT (vertical axis in the figure). If properties of the test piece are identical to the reference standard, the point of light is positioned to the center of the CRT. Movement of the point of light in the horizontal direction represents changes in conductivity. Movement in the vertical direction represents changes in dimension or permeability. If the permeability of the test piece is considered equal to that of the reference standard, vertical movement represents dimensional changes.


REFERENCE STANDARD
TEST PIECE
PROCESSING CIRCUITS
Point of light
CRT
AC


From here
To here
Means
Conductivity change
Dimension change
Conductivity and dimension change

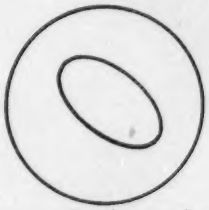
Phase Analysis - Ellipse Method

Phase analysis by the ellipse method provides the CRT patterns illustrated in Figure 32-5-26. This method uses two coils arranged for either external or self-comparison. When outputs of the coils are equal, the CRT indication is a straight line. Orientation of this straight line is adjusted to establish a reference position. Dimensional changes cause the straight line to rotate such that its orientation from the reference position is indicative of dimensional changes. Conductivity changes cause an ellipse to form whose size is proportional to the extent of conductivity change. Changes in both dimensions and conductivity form an ellipse at an orientation away from the reference position.

Reference Position Only

Dimensional Change Only

Conductivity Change Only



Conductivity and Dimensional Change

Figure 32-5-26. Ellipse Indications

Phase Analysis - Linear Time Base Method

Phase analysis by the linear time base method uses a phase controlled timing voltage to establish the horizontal sweep on the CRT. The period of the timing voltage is equal to the time (period) of one cycle of output from the test coils. The output of the two test coils is applied to the vertical axis of the CRT. When no output exists, i.e., when the test coils are balanced, the CRT display is a horizontal line caused by the timing voltage. When the test coils are unbalanced, the output is reflected as a sinusoidal waveform on the CRT. Because the periods of the timing voltage and the test coil output are equal, one full cycle of test coil output appears on the CRT. The starting point of the cycle is selected by adjustment of the phase relationship of the timing voltage with respect to that of the test coil output. Figure 32-5-27 illustrates typical patterns.

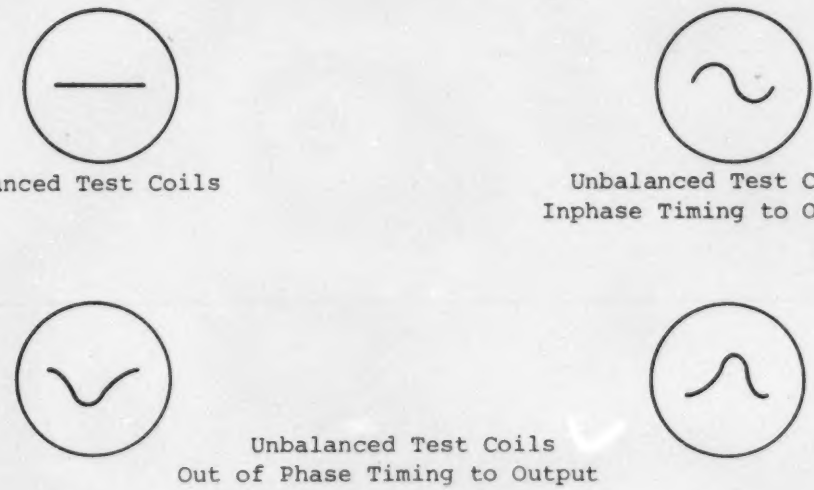


Figure 32-5-27. Linear Time Base Signals

Linear time base processing circuits reflect changes in dimensions of the test piece as changes in amplitude of the sine wave and changes in conductivity as changes in phase of the sine wave. Thus, the system has capability of separating these variables.

A common technique for aiding in the interpretation of linear time base signals is the use of a slit placed over the CRT screen. As illustrated in Figure 32-5-28, only the portion of the sine wave visible in the slit is of concern. For measurements of conductivity, a known test piece is tested and the phase control is adjusted until the zero reference of the sine wave appears in the slit. If conductivity of additional test pieces differs from the known test piece, a phase shift occurs. This is seen in the slit as a change from the reference value. Dimensional changes would not cause a phase shift and therefore not be seen in the slit.

Figure 32-5-28. Use of Slit for Linear Time Base

Modulation Analysis

Modulation analysis uses relative motion between the test coil and the test piece and evaluates modulation of test coil output caused by this relative motion. A differential coil in the self comparison arrangement is affected by test piece characteristics as with other methods of eddy current testing. In addition, due to the relative motion, the rate

of change in test coil output is proportional to the rate of change of the material variable causing the output. Thus, coil's output is modulated proportional to the rate of change of the material properties of the test piece.

Material properties vary over the length of the material at different rates. Thus, different modulation frequencies are caused by various properties. Dimensions of material forms, such as tubing, are typically very uniform, i.e., dimensions change very slowly along the length of the article. Thus, dimensional changes are characterized by very low frequency modulation. Chemical composition and heat treatment changes occur slowly and, therefore, cause low frequency modulation. Changes in lattice, caused by material processing such as cold working, occur over relatively small areas and, therefore, cause intermediate frequency modulation. Material discontinuities are typically small in size or have sharp boundaries and thus cause high frequency modulation.

Modulation analysis circuits contain electronic filters which permit display of frequency ranges. For example, selection of high frequencies for display results in indication of discontinuities and suppression of signals from other material properties. In addition, phase analysis circuits are typically included to suppress either conductivity or dimension effects. These performance characteristics make modulation analysis exceptionally good for detection of discontinuities because other variables are highly suppressed. However, speed control and alignment of the test piece with the test coil are essential in order to avoid false indications.

EXERCISES

1. Explain the relationship between permeability, magnetic flux density and intensity of the magnetizing force.

2. Explain the relationship between the number of turns and the spacing of turns of a coil to the inductance or inductive reactance of the coil.

3. Briefly describe how eddy currents are generated.

4. Describe the effects on eddy current by:
   a. magnetic field strength
   b. test frequency
   c. conductivity of the test piece
   d. permeability of the test piece

5. What are some of the factors which affect the conductivity of a metallic alloy?

6. Explain why eddy current testing of magnetic alloys must be performed with the alloy magnetically saturated.

7. Briefly explain the following regarding eddy current testing:
   a. lift-off effects
   b. fill factor effects
   c. fall-off effects
   d. end effects

8. Describe the physical arrangements of surface coils, including gap coils and spring loaded coils.

9. Briefly explain the use of differential coils in the self-comparison technique and the external comparison techniques.

10. Briefly explain the impedance analysis method of eddy current testing.

11. Compare and contrast the following:
    a. Vector point method of phase analysis
    b. Ellipse method of phase analysis
    c. Linear time base method of phase analysis

12. Describe modulation analysis and briefly explain its use.

MATERIALS

Not Applicable

PROCEDURES

Not Applicable

DATA TABLE

Not Applicable

REFERENCE MATERIALS

Hugo L. Libby, Introduction to Electromagnetic Nondestructive Test Methods, 1971, Wiley-Interscience

R. L. Brown, Inservice Examination of Heat Exchanger Tubing with Eddy Current NDT Equipment, HEDL-TME-75-29, National Technical Information Service, Springfield, Virginia

J. H. Flora, S. D. Brown, J. R. Weeks, Evaluation of the Eddy Current Method of Inspecting Steam Generator Tubing, 1976, National Technical Information Service, Springfield, Virginia

General Dynamics, Eddy Current Testing Classroom Training Handbook, General Dynamics, Convair Division, San Diego, California

Owen F. Hedden, Short Course on ASME Section XI Eddy Current Examination, 1979, American Power Conference

TEST

1. Define:

   a. permeability

   b. conductivity

   c. magnetic flux density

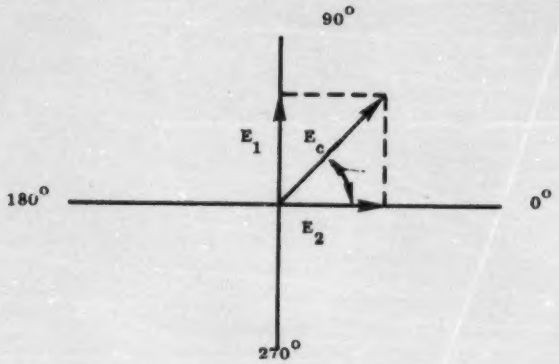
   d. inductance

   e. inductive reactance

2. Circle the letter of each of the following conditions which would provide for an increased inductive reactance.
   a. fixed coil, increased frequency
   b. increased number of turns per inch of coil length
   c. greater spacing between individual turns of wire
   d. double winding vice single winding.

3. Identify the following terms represented by Graph #1 below.
   a. E_1
   b. E_2
   c. Ec

d.



Graph #1

4. Referring to Graph #1, the illustrated plot is:
   a. voltage plane
   b. impedance plane
   c. inductance plane
   d. eddy current plane

5. Referring to Graph #1, circle the letter of each of the following conditions which would increase ϕ.
   a. use of coil with greater inductive reactance but same resistance
   b. addition of resistance to the circuit
   c. rewinding the given coil such that closer spacing between turns is achieved
   d. replacing the given coil whose ratio XL/R is 15 with a coil whose ratio XL/R is 10

6. Describe how eddy currents are generated.

7. Describe the effect on eddy current penetration depth by:
   a. magnetic field strength

   b. test frequency

c. conductivity of test piece

d. permeability of test piece

8. Name five factors which affect conductivity of a metallic alloy.

9. Describe why eddy current testing of magnetic alloys requires magnetic saturation of the alloy.

10. Describe the effects of:
    a. lift-off

    b. fill factor

    c. fall-off

    d. end effects

11. Describe the following coil techniques with respect to eddy current testing:
    a. absolute coil

    b. self-comparison differential coil

    c. external comparison differential coil

12. Describe the following eddy current testing methods.
    a. impedance analysis

    b. vector point phase analysis

c. ellipse phase analysis

d. linear time base phase analysis

13. Describe how phase analysis circuits distinguisy between the conductivity variable and the dimension variable.